学校编码：10384　　分类号______密级______

学号：200329019　　UDC ______

厦门大学

硕　士　学　位　论　文

A Study on High isolation RF MEMS Switch

高隔离度射频微机电开关的研究

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专　业　名　称：测试技术及计量

论文提交日期：2008　年　　月

论文答辩时间：2008　年　　月

学位授予日期：

答辩委员会主席：__________

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2008 年　月

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ABSTRACT

Microelectromechanical system (MEMS) technology has been developing for about two decades. It has been integrated into many existing designs, including radio frequency (RF) microswitches. As early as 1971, when the first RF switches were built using commercial technologies, its designs have developed and improved dramatically. The newest switches that are fabricated and tested today, using MEMS technology, operate at radio, even microwave frequency. An optimal RF MEMS switch is one with high isolation and operational life of millions of cycles. This work of the thesis is aimed at developing a switch with near optimal performance.

Details regarding the design of RF MEMS switches for improving isolation and reliability are addressed. In addition, detailed processing techniques and fabrication concerning RF MEMS switches are investigated.

The performance of this thesis is as following:

Chapter 1, The switch parameters, classification, typical fabrication , performances and design considerations are introduced.

Chapter 2, A new type of high isolation metal to metal contact switch with cantilever beam is presented. The relation between the pull-down voltage for the switches actuation and the curve of the cantilever beam is simulated. The natural frequency and stress distribution of some micro-switches with different structures are also analyzed.

Chapter 3, Fabrication and process designs of the metal to metal contact series RF MEMS switches with diaphragm structure and electrodes fixed in the substrate are developed and discussed. Various process and fabrication design issues are also addressed in this chapter.

Chapter 4, The contribution from this research is discussed and some suggestions for the future research are presented.

Keywords: MEMS switch, High isolation, Silicon, Fabrication process

摘 要

微机电系统（MEMS）是国际上近二十年来新兴的一项热门技术。射频（RF）MEMS 器件可以认为是用 MEMS 技术实现的、用于从低频到红外线以下频段信号的产生与处理的微型化可集成器件，这其中就包括了微机电射频开关。从 1971 年第一个射频开关被制作出来至今，射频开关的研发已经取得了很大的进展。理想的射频开关应具有高的隔离度和数百万次的循环使用寿命。本课题的任务就是设计并制作一种这样的开关。

本论文对高隔离射频开关的结构进行了设计、分析和讨论，并详细论述了制作过程中的工艺步骤。

全文共分为四章：

第一章介绍了开关的参数、分类、一些典型开关的性能和制作工艺，最后还谈到了开关设计中要考虑到的某些问题。

第二章设计了一种新型的悬臂梁结构的高隔离度金属接触式开关，并模拟了开关的驱动电压和悬臂梁变形之间的关系曲线。分析和比较了悬臂梁结构、桥结构和四边固支的壳结构开关的固有频率，及驱动中产生的最大应力大小和应力分布。

第三章设计了四边固支壳结构、电极嵌入式开关的模版和工艺流程，确定使用材料和最适合的制备方法。制备开关并论述了几个在制作过程中遇到的问题及解决办法。

第四章对整个论文进行总结。

关键词： 微机电开关、高隔离度、硅、制造工艺

Contents

目录

CHAPTER 1 Introduction

1.1 Motivation for RF MEMS Switch

Wireless communication has made an explosive growth of emerging consumer markets, as well as in military applications of RF, microwave, and millimeter-wave circuits and systems. These include wireless personal communication systems, wireless local area networks, satellite communications, automotive electronics, etc.[1]. In these systems, the RF switch is one of the essential components to handle RF signals. Previously, RF switches have been implemented by using p-i-n diodes and GaAs MESFETs in the form of junction field-effect transistor (JFET)-based semiconductor switches. However, these semiconductor switches show poor performance in the respect of signal loss and power consumption as the frequency increases. Recently, RF microelectromechanical system(MEMS) switches have been envisaged to be perfect devices for such a wide range of commercial and military communication applications with portable sizes and wide-band reconfigurability owing to their outstanding performance such as high linearity, high quality factor, low loss, and low power consumption.

1.2 What are RF MEMS switches?

1.2.1 Conception of RF MEMS switches

RF MEMS switches are specific micro-mechanical switches which are designed to operate at RF to mm-wave frequencies (0.1to 100GHz)[2].

Some important parameters to be considered in the design of RF switches are as follows:

●Isolation

The isolation of a switching system is specified when there is no signal transmission. This is also measured as S_{21} between the input and output terminals of the switched circuit, under the no-transmission state or when the switch is in the off condition. A large value indicates very small coupling between input and output terminals. Thus the design goal is to maximize the isolation. In RF MEMS switches isolation may degrade as a result of proximity coupling between the moving part and the stationary transmission line as a result of leakage currents.

●Insertion loss

The insertion loss of an RF device is a measure of its efficiency for signal transmission. In the case of a switch, the insertion loss is specified only when its state is such that signal is transmitting or when the switch is in the on state. This is specified in terms of the transmission coefficient, S_{21}, in decibels, between the input and output terminals of the switched circuit. Usually specified in decibels, one of the design goals for most of the RF switches is to minimize the insertion loss. The insertion loss tends to degrade with increase in frequency for most of the solid-state switching systems. Compared with these, RF MEMS switches can be designed to operate with a small insertion loss at several gigahertz. Resistive losses at lower frequencies and skin-depth effects at higher frequencies are the major causes for losses.

●Transition time

The transition time is a measure of speed with which the position of a switch can be toggled. This is defined as the time required for the output RF signal to rise from 10% to 90% of its value for off-to-on transition and 90% to 10% for on-to-off transition. In other words, it is the time taken for the output voltage to change to within 1 dB of the final state.

●Switching rate

The switching rate also represents the time for toggling from one state of the switch to another. However, in this case, the time is measured from 50% on the control voltage to 90% of the RF envelop when the switch is turned on. Similarly, when the switch is turned of, the time is measured till the RF signal voltage reaches 10% of the original. Hence, the switching rate is the time required for the switch to respond at the output due to the change in control voltage. The switching rate, also referred to as switching speed, is always larger than the transition time of a switch.

●Actuation voltage

All automated systems require a control signal for actuation. Depending on the scheme and its efficiency, these voltages vary significantly. But this is not a big problem with semiconductor-based switching systems. One of the design objectives of state-of-the-art electromechanical switching systems is to bring these voltages down to the level compatible with the rest of the circuit[3].

1.2.2 Switch types

RF MEMS switches generally could be divided into three classes according to their contact methods、circuit configuration and actuation mechanism.

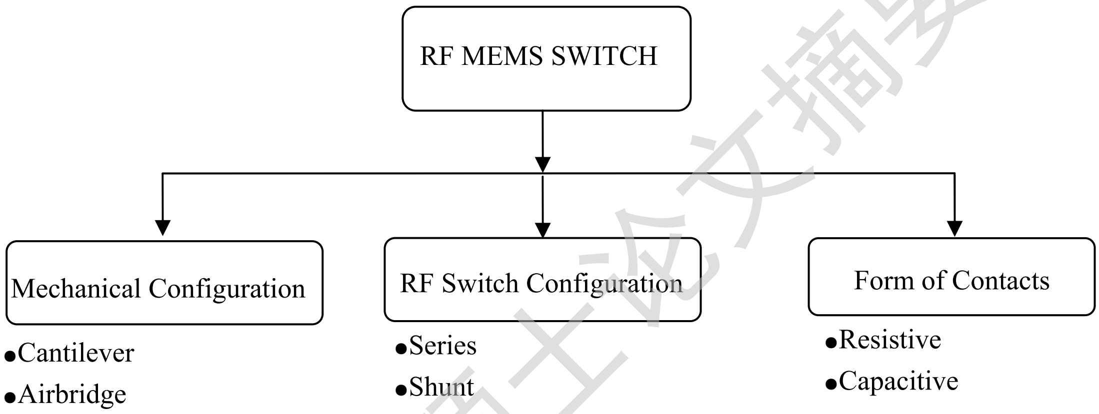

Fig.1.1 Physical configuration of RF MEMS switch

1) They are usually categorized by the contact methods capacitive (metal-insulator-metal)[4-6] and resistive (metal-to-metal)[7-9]. Capacitive switches use a thin layer of dielectric material to separate two conducting electrodes when actuated. The dielectric layer prevents direct metal-to-metal contact. Metal-to-metal switches utilize physical contact of metal with low contact resistance to achieve low insertion loss when actuated[10].

2) The two basic MEMS switch types from a function perspective are series switches and shunt switches[11], as shown in fig.1.1. There are two types of MEMS series switches: the broadside series switch and the inline series switch. The actuation of the broadside switch occurs in a plane that is perpendicular to the transmission line, while the actuation of the inline switch occurs in the same plane as the transmission line. The main difference between the two designs is that the RF signal will pass by the entire inline switch[12]. The series switches are usually realized as metal-contact

switches able to switch signals from DC to radio frequencies with high isolation. Most implementations of the shunt switch type are based on tunable capacitors short-circuiting the signal line in the on-state[13].

3) The forces required for the mechanical movement can be obtained using electrostatic, electromagnetic, piezoelectric or thermal designs. To date, only electrostatic type switches have been demonstrated at 0.1-100 GHz with high reliability (100 million to 10 billion cycles) and wafer-scale fabricating techniques[14].

1.3 Fabrication and performance of MEMS DC-contact switches

1.3.1 Fabrication

The fabrication of MEMS DC-contact switches is more involved than standard capacitive switches due to the need to define a specific contact region and a contact metal. Also, the pull-down electrodes are separated from the contact region, which results in additional mask layers. The following two DC-contact switches were developed in 2004.

The entire fabrication procedures are as follows: First a 1 *um*-thick silicon dioxide (SiO_2) layer was grown using wet thermal oxidation on a (100)-oriented p-type Si substrate. A 0.3 *um* thick aluminium was deposited for a bump layer. A 0.3 *um* thick aluminium and 0.2 *um* thick gold coplanar waveguide transmission line was then fabricated. Next, a 0.2 *um* of silicon dioxide was deposited over the ground electrode with RPCVD. This oxide layer blocked the DC control signal from shorting out during switch activation. A 1 *um* photoresist was spun for the sacrificial layer. The window for the cantilever beam was opened with photolithography. A chrome (0.02 *um*), gold (0.2 *um*), and aluminium (0.3 *um*) were subsequently deposited for the cantilever beam, followed by wet etching for pattern. Gold was chosen as the contact material of the switch because it has excellent surface insertness, so it does not form a native oxide. Sacrificial layer were dissolved in acetone and then rinsed in isopropyl alcohol. A 0.02*um*-thick chrome layer underneath gold was wet-etched for gold-to-gold contact. Deionised water was not used during the final rinse process to avoid the stiction problem. Rinsed devices were dried on a hot plate in air. Finally, the device was cleaned by oxygen plasma in an RIE chamber.

As shown in fig.1.2, the switch has low pull-in voltage of 15V and fast switching speed of 60 *us*. The insertion loss is -0.18 *dB* at 30 *GHz*. The switch isolation is -50 *dB* at low frequencies, and decreases slowly to -30 *dB* at 30 *GHz*[15].

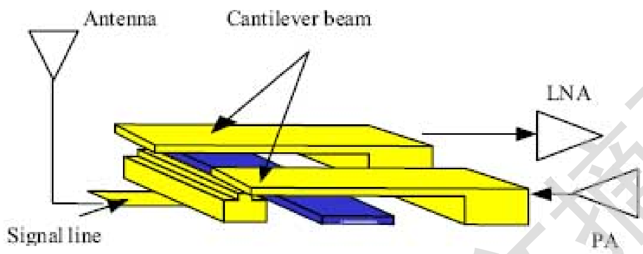

Fig.1.2 Optical microscopic image of the fabricated RF MEMS switch[15]

As shown in fig.1.3 the switch consists of two gold beams, namely the lower and upper beams. The lower fixed-fixed beam is t_l=0.7 *um* thick, d_l=320 *um* long, w_l=20 *um* wide and is suspended g_l=2 *um* above a 50/80/50 *um* coplanar waveguide (CPW) line. The two anchor points of this fixed-fixed beam are connected to the ground planes of the CPW line. The second beam (upper beam) is suspended g_u=5.5 *um* above the lower beam, has no anchor points attached to the substrate, but is connected to the middle of the lower beam. Although the upper beam is d_u=1 *mm* long, it is very stiff, because it is made of t_u=13 *um* of electroplated Au.

The fabrication starts with sputtering and patterning of Cr/Au 0.025/0.9 *um* that is performed to define the 50/80/50 CPW lines and the biasing electrodes. PECVD deposition of 0.3 *um* Si_3N_4 follows, which is patterned with a dry RIE process. This dielectric layer is mainly deposited to protect the actuation pads from potential direct contact with the upper beam. The first sacrificial layer is subsequently spun at 3.5*krpm* and patterned. This sacrificial layer is post-baked at a 180℃ Hotplate for 3.5

min to avoid any out-gasing in the remaining of the process. The lower beam deposition and patterning follows. This beam is made of low-stress 0.7 *um* Au and is anchored at the CPW ground planes. A second sacrificial layer is spun at 3*krpm* and patterned. This photoresist results in a 5.5 *um* layer after being post-baked in a 150℃ oven for 1*h*. A thin layer of low stress Au is subsequently sputter deposited on top of the second sacrificial layer. This layer is electroplated to 13 *um* to create the very stiff upper beam. The final steps are the etching of the sacrificial layers and drying of the devices with a conventional supercritical CO_2 process[16].

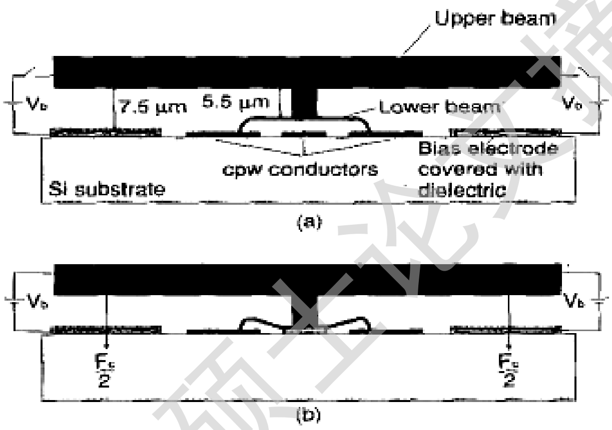

Fig.1.3 (a) Schematic diagram of the proposed microfabricated device when no bias voltage is applied (b) Schematic representation of the device while in the down state[16]

1.3.2 Performance

Spring-Loaded DC-Contact RF MEMS Switches: As shown in fig.1.4, the metal-to-metal contact RF MEMS switches are electrostatically actuated, but the DC-contact is achieved through a stress-originated force. The contact resistance is not related to the actuation force and only depends on the residual stress in the switch. The switch insertion loss has been measured to 0.05 *dB* at 2 *GHz*, which corresponds to an on-state RF contact resistance of 0.5Ω. Additionally, the switch provides an off-state isolation of 38 and 13 *dB* at 2 and 40 *GHz*, respectively[17].

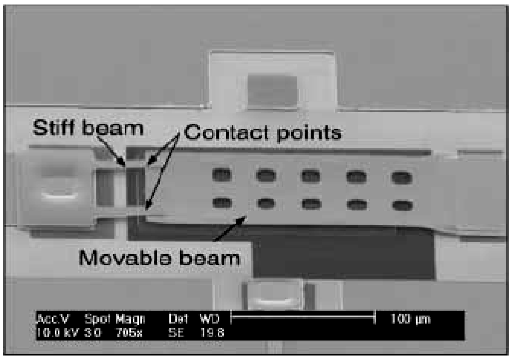

Fig.1.4 Microphotograph of a fabricated switch[17]

Single Crystalline Silicon RF MEMS switch using SiOG process: As shown in fig.1.5, single Crystalline Silicon RF MEMS switch for obtaining higher productivity and uniform characteristics compared with conventional metal switch, was designed and fabricated using SiOG(Silicon on Glass) process. By using SiOG substrate instead of a SOI substrate, fabrication cost can be significantly reduced. The proposed switch is fabricated on CPW and actuated by electrostatic force. Measured pull-in voltage was 19V and 18 samples of measurable 20 samples showed variation less than 15% on average value of the measured voltages. Forming damping holes on the upper electrode led to a relatively fast switching speed. Measured ON and OFF time were 25 *us* and 13 *us*, respectively. After 108 cycles repeated actuation, stiction problem was not occurred. But contact resistance was hanged with about 0.5 to 1 *ohm*. The RF characteristics of the fabricated switch with 0 to 30 *GHz* are measured. The isolation and insertion loss measured on the 4 samples were -38 *dB* to -39 *dB* and -0.18 *dB* to -0.2 *dB* at 2 *GHz*, respectively[18].